8 Accelerator Tubes

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8.1 Introduction

The accelerator tube fulfils two complementary functions. As a high-vacuum insulator, it is required to support the highest possible fields. As a beam transport element, it must transmit and focus the particle beam with minimum degradation and loss.

The ideal tube, as an insulator, has the following properties:

(a) it can sustain the same voltage gradient as the gas that surrounds the terminal and column, and the insulators which support them;
(b) it is undamaged by sparks and transients;
(c) it can operate at full gradient with little or no conditioning.

As a beam transport element,

(d) it should transmit intense beams of high emittance without loss;
(e) the focusing action must be predictable and allow for good transmission of beams with different masses, energies and charge states;
(f) scattering should be small and aberrations unimportant;
(g) it must generate negligible ionizing radiation, with or without beam, and
(h) it should be unaffected by fluctuations and inhomogeneity in the column gradient.

In addition, it should have a high vacuum conductance, be rugged, compact and cheap, and last for ever.

Practical accelerator tubes fall far short of the performance of this paragon, despite seventy years of progress in understanding beam optics and vacuum insulation. Nevertheless, tube design has advanced, in spite of the difficulty of carrying out systematic studies and potentially destructive tests on operating accelerators. To these problems of cost and accessibility must be added the difficulty of interpreting data from rapid breakdowns occurring inside a closed pressure vessel.

In spite of this, tubes are now available which meet the tight specifications for voltage-holding, beam transport and reliability demanded in modern analytical and industrial accelerators.

8.2 Physical Processes Occurring in Vacuum High-Voltage Systems

An accelerator tube is made up of one or more annular insulators, bonded to metal electrodes, across which the high voltage is applied to accelerate particles through a series of central apertures. In the earliest, air-insulated accelerators, the insulators were long glass or porcelain tubes sealed to metal disks that carried cylindrical electrodes, almost as long as the insulators, through which the beam was focused and accelerated. To avoid tracking in damp air, the maximum field along the outside of the insulator was very much lower than that in the gap between the cylindrical electrodes. The importance of subdividing long insulators into short rings capable of sustaining higher fields was early recognized by Breit at the Department of Terrestrial Magnetism in Washington, even before the first nuclear experiment with an accelerator or the first use of compressed gas as an insulator. The essential features of such a multielement tube are shown in Fig. 8.1. The electrodes are thin relative to their spacing and may be flat or dished, in order to decouple the beam from the insulator. The insulators may be cylindrical or convoluted on the inner surface. The electrodes are bonded to the insulators either by a thin layer of thermoplastic adhesive, such as polyvinyl acetate, or by a diffusion bond of aluminum foil formed under sustained high pressure and temperature.

The processes that lead to breakdown and therefore limit the maximum operating field of an accelerator tube have been discussed by Hyder [2], Chatterton [3], Juttner [4], Latham [5] and Joy [6], among others. In clean,

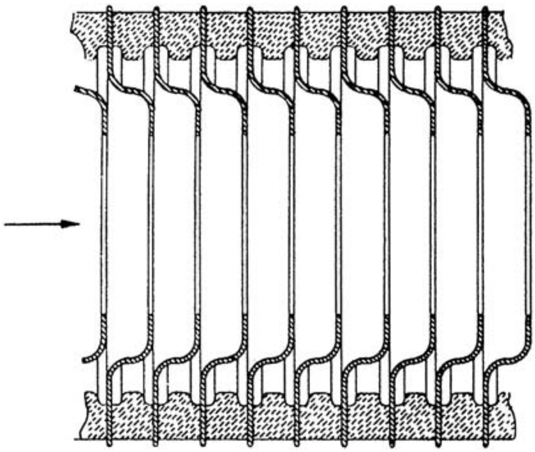


Fig. 8.1. Conventional one-inch-pitch accelerator tube, from [1]. Insulators: borosilicate glass with convoluted profile. Electrodes: dished, polished aluminum. Bond.: thermoplastic polyvinyl acetate resin

dry compressed gas, breakdown across the external surface of the insulator only occurs if the surface is defective or if a voltage surge raises the field instantaneously high above the working value. Similarly, the high dielectric strength of the insulator precludes volume breakdown unless there are defects in the bond between insulator and electrode or in the insulator itself. The areas of concern are therefore the inner surface of the insulator and the vacuum space between the electrodes.

8.2.1 Surface Effects

The tangential field across the surface of a cylindrical insulator between two plane electrodes will be uniform if the surface resistance is constant and the surface charge zero or uniform. If the surface is convoluted the field will vary. Electrons are always present to some degree, and the applied field will accelerate some of them towards the insulator. On their striking the insulator, secondary-electrons may be ejected. If the secondary-electron coefficient is less than one, the surface becomes negatively charged; if greater than one, a positive charge develops. Since the secondary emission coefficient is energy-dependent, and since electrons that strike near the cathode will tend to have lower energy than those near the anode, the surface charge, and consequently the tangential field, will not be uniform. Ion bombardment also liberates secondary electrons, and when electrical activity liberates ions from the electrodes, surface charging of the insulators will increase. Some possible paths for secondary particles are indicated in Fig. 8.2.

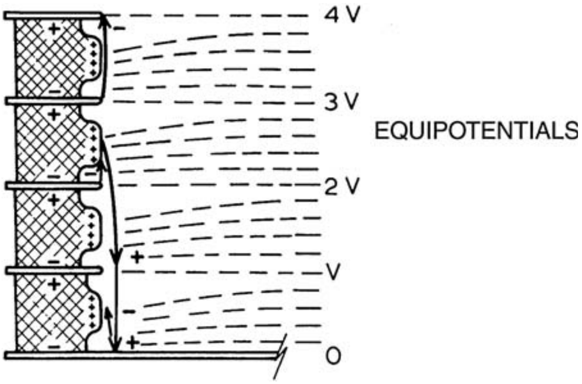


Fig. 8.2. Paths of secondary electrons and ions, showing field enhancement due to buildup of surface charge on the insulators, from [2]

An even weaker point than the insulator surface is the triple junction between vacuum, insulator and cathode. The possible situation in a tube with glass insulators and a polyvinyl acetate (PVA) bond is shown in Fig. 8.3. If

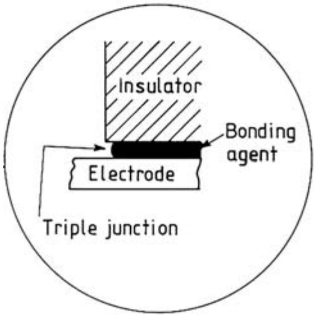


Fig. 8.3. High field near the triple junction, resulting from the glue film having a low dielectric constant and being recessed behind the insulator (Reprinted from [6], copyright (1990) with permission from Elsevier)

the glue film does not extend beyond the insulator, there is a region between insulator and cathode where the field is higher than that in the glass by a factor ϵ (= 4–5), the dielectric constant of borosilicate glass. This leads to enhanced emission of electrons from the triple junction and thus increased surface charging of the insulator. If the glue extends beyond the insulator, as it usually does, the high field is eliminated but hydrocarbon polymer is exposed to the field and to secondary particles in the main gap. In either case this is a weak point in the system.

The alternative method of construction relies on a thin aluminum foil placed between and diffusion-bonded to the electrode and the ceramic (high-density alumina) insulator. If the foil does not reach beyond the insulator, there is likely to be a microscopic void between the insulator and electrode at the edge of the foil with a field enhancement of as much as 8–9 (the dielectric constant of alumina). The edge of the foil may further increase the field at its junction with the insulator. If the foil protrudes beyond and does not adhere to the electrode, its sharp edge may again act as a stress raiser unless chemical or other means have been successful in blending it into the electrode. Any enhanced field in this region will act as a source of electrons to charge up the insulator surface.

One of the familiar symptoms of these problems is the presence of hair-line track marks across the insulators of used tubes, caused by a discharge of the limited energy stored between adjacent electrodes. Such track marks are usually superficial and have little or no effect on the voltage-holding capability of the insulator. However, repeated discharges may eventually result in glass spalling and damage to the bond material, culminating in failure of the section to hold voltage, as seen in Fig. 8.4. Damage of this nature is often confined to sections near the terminal or the intershield, if there is one, where tank sparks induce large and rapid transients and overcome the protection offered by the spark gaps.

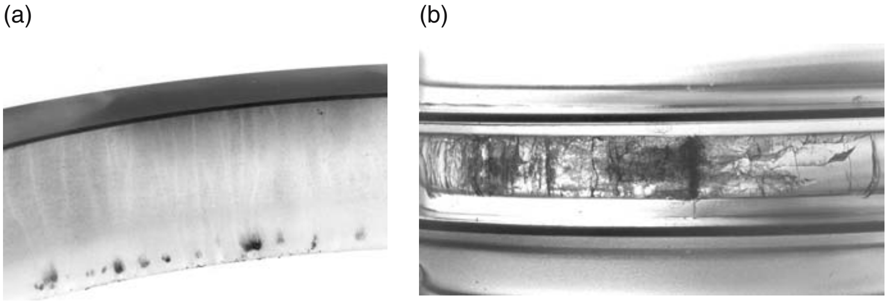


Fig. 8.4. (**a**) Hairline tracks and aluminum deposits sputtered from the cathode. (**b**) Glass damage resulting from arc discharges and tracking

One answer to these problems is to modify the shape of the insulator surface. Replacing a straight cylindrical Lucite insulator by a truncated cone was shown to improve voltage-holding between polished copper electrodes subjected to pulsed voltages, as seen in Fig. 8.5 [7, 8]. The effect is similar whether the insulator tapers towards the cathode or the anode, but the conditions are very different from those in an accelerator tube. A more effective practice is to convolute the inner surface of the insulator so as to increase the tracking length and to create regions of low field. Care has to be taken to ensure that these convolutions do not actually increase the field at the triple junction and to ensure adequate protection against rapidly rising overvoltages from tank sparks, which can shatter glass if not diverted.

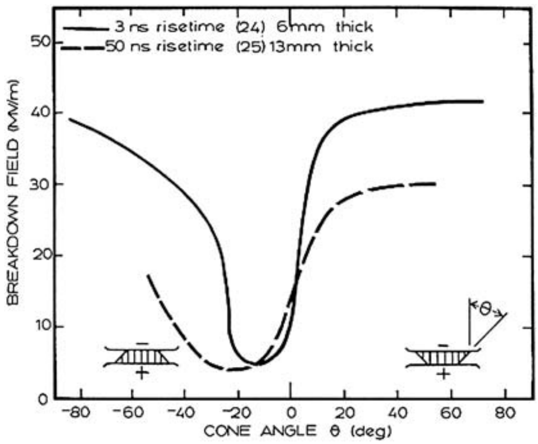


Fig. 8.5. Impulse breakdown strengths of conical Lucite insulators separating polished copper electrodes, as a function of cone angle (Reprinted from [3], copyright (1984) with permission from Elsevier)

8.2.2 Discharges in Vacuum

Juttner [4] has reviewed the different initiating processes that precede breakdown. He divides breakdown into a prebreakdown stage, an ignition stage, a current growth stage and an arc stage. There is a sharp division between the prebreakdown stage, with an upper current limit of a few mA, and the high-voltage breakdown or low-voltage arc, with a minimum current of several A. The former can be sustained solely by electron emission. The latter requires a plasma to develop, as shown in Fig. 8.6.

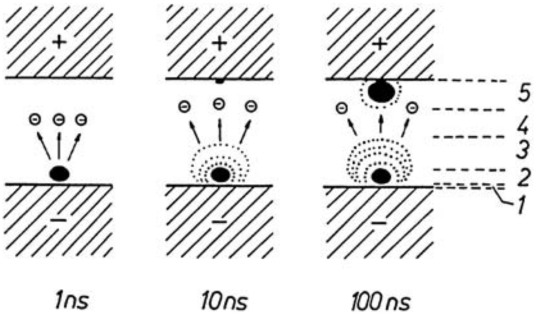


Fig. 8.6. Discharge development in different regions of the gap, from [4]: 1, space charge sheath; 2, plasma flare; 3, expanding plasma; 4, vacuum zone; 5, anode flare (Reprinted from [4], copyright (1988) with permission from Elsevier)

Electron emission from metal surfaces is described by the Fowler–Nordheim law, $i = AV^2 \exp(-B/V)$, where V is the gap voltage and A and B depend on the geometry, material and surface condition of the electrodes. At the fields of 1–3 MV/m typical of accelerator tubes, Fowler–Nordheim currents are very small; field enhancements of 10^2 to 10^4 are needed to produce currents sufficient to initiate breakdown. Sharp points or edges on the metal surface might be expected to raise the field sufficiently to emit copiously, but care is taken in manufacturing to achieve a smooth finish free from asperities. Electrodes that suffer discharges in operation, however, may suffer irreversible damage in the form of arc craters with sharp rims. However, electron-microscopic studies of high-voltage test electrodes have shown that electron emission often arises from point sources where the surface is smooth and featureless. It is assumed that these emitters are at the edges of small regions of insulating material where the potential barrier preventing emission is lowered and the energy of the electrons is increased to allow tunneling through the barrier [6], as indicated in Fig. 8.7. Adsorbed gas on the electrode surface may be one of the sources of these inclusions. Small loosely bound particles, especially conductors, may also contribute to electron emission and to the subsequent development of a full arc.

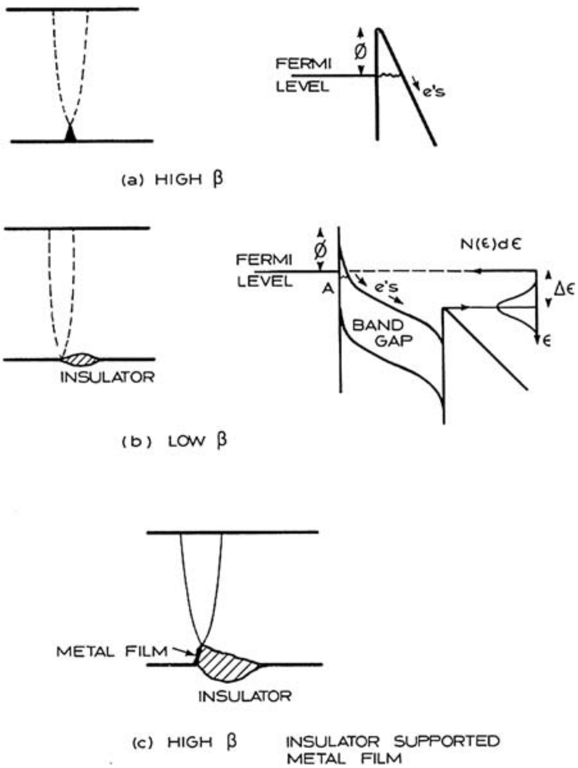


Fig. 8.7. Possible emitter structures and electron energy levels (Reprinted from [3], copyright (1984) with permission from Elsevier)

However carefully electrodes are polished and cleaned, the residual pressure in an accelerator tube, due to permeation, outgassing and particle bombardment, is likely to remain in the range 10^{-3} to 10^{-5} Pa. At these pressures monolayers will form on electrode and insulator surfaces in seconds. The surfaces will always be covered with a layer of weakly bound adsorbed gas molecules, in addition to any debris or impurities left behind from manufacture or cleaning. As the gap voltage is raised, the probability of stray ions gaining energy and releasing particles of the opposite sign on impact increases. If the number of negative ions released for each positive-ion impact is K^- and the number of positive ions from each negative-ion impact K^+, then, when $K^-K^+ > 1$, a divergent chain reaction will take place, releasing an increasing quantity of neutral gas into the gap, as well as the ions which drive the reaction. Electrons will also take part, adding to the current, but the ions are responsible for most of the gas release. As the current grows, the voltage across the gap (fed from the resistor chain, which is a high-impedance source) decreases, slowing the process. At the same time, the surface gas density declines, multiplication ceases and the process ends.

The theory of these microdischarges is due to Gerasimenko [9], who calculated typical durations of a few hundred μs. Experiments by Schefer and Chatterton [10] have confirmed and extended this model, drawing attention to the effect of surface contaminants such as carbon on the multiplication factor of the chain reaction. At the end of the discharge, some molecular contaminants will have been dissociated and some of the desorbed gas pumped away. The electrode is subsequently able to withstand a higher field.

The relative importance of emission from asperities, from dielectric inclusions, from clumps and particles and from adsorbed gases is disputed and must, in any case, be dependent on the materials of construction, the geometry and even the operating procedure.

8.2.3 Total-Voltage Effects

The processes described above occur within a region composed of a single insulator ring bonded at each end to electrodes. In this region the voltage is limited to ∼50 kV or less, except for transient overvoltages following machine sparks. But, as ambitious designers soon found, attempts to reach higher voltages by increasing the column length and maintaining the same potential gradient were unsuccessful as soon as the tube was installed. Something was happening in the tube that depended on the total voltage, not just the field.

When a beam is present, scattering by the residual gas will give rise to ions and electrons. Some of the ions may hit electrodes in the tube, triggering energy-dependent processes leading to breakdown. Electrons stopped by the tube electrodes or beyond the end of the tube will produce bremsstrahlung, the intensity depending linearly on the atomic number of the target and more strongly on the electron energy. The resulting ionization is concentrated near the positive end of the column and consequently perturbs the column gradient. It may eventually increase enough to exceed the output of the charging system, causing the voltage to collapse. Even in the absence of a beam, stray ions and electrons may enter the tube from outside or be released near the edges of beam apertures. Some may travel long distances, gaining enough energy to initiate discharges. Measures designed to reduce or eliminate these effects are discussed in Sect. 8.3.

In 1952 Cranberg [11] reviewed the published data on breakdown voltage across gaps ranging in length from 0.1 mm to 5 m. He suggested that the observed reduction in breakdown field with increasing gap length could be due to the presence of small clumps of loosely bound material. Such clumps might, by electrostatic repulsion, be injected into the gap and gain enough energy to evaporate hundreds of atoms at the point of impact, resulting in an arc discharge.

His theory predicted that the breakdown voltage would vary as the square root of the gap length for a given pair of electrodes, in rough agreement with the existing data. Subsequent work has identified several possible processes, depending on particle mass and terminal velocity [12]. The critical parameter is the ratio of the terminal velocity v_t to the plastic velocity v_p of the electrodes. Below v_p particles rebound elastically; above v_p the collision is inelastic, resulting in gas desorption and sometimes melting, crater formation and evaporation. The plastic velocity depends only on the yield strength and density of the material; see Table 8.2.

Considering the case where the total voltage available is, at most, that across a few pitches, four types of event can be distinguished in order of increasing radius r:

(i) $v_t \gg v_p$, and typically $r < 0.1\,\mu\text{m}$. Such particles vaporize on impact, but the number of neutrals and ions released is too small to initiate breakdown.

(ii) $v_t \geq v_p$, $0.1 < r < 10\,\mu\text{m}$. These particles can cause local melting and evaporation, liberating neutrals, ions and liquid droplets. The more energetic ones may produce enough gas and ionization to trigger breakdown. Field enhancement at crater lips and protrusions may give rise to cathode instability.

(iii) $v_t < v_p$, $10 < r < 50\,\mu\text{m}$. These particles are too slow to trigger breakdown in a single transit. Multiple bouncing impacts with charge exchange might increase their energy to bring them into category (ii).

(iv) $v_t \ll v_p$, $r > 50\,\mu\text{m}$. If such a large, slow particle approaches a cathode (or anode) protrusion, the enhanced field in the gap between particle and protrusion may result in enough current flow for melting and evaporation to take place by the Joule or the Nottingham effect.

Many observations, mostly in gaps of a few mm, have been made with the object of clarifying the importance of these processes; see, for example, Chatterton and Eastham [13]. These authors found that, after careful surface treatment and thorough cleaning, large microparticles are rare and multiple transits and bouncing unimportant. By contrast, small particles are abundant and often appear to be weakly bound [14]. These seem to give rise to more frequent breakdowns than would be expected on the basis of the above classification. Spark conditioning, however, can reduce the microparticle yield to zero except when the gap is on the verge of breakdown.

Like microdischarges, which depend on ion exchange, microparticle processes are energy-dependent and can be reduced, if not eliminated, by careful conditioning and limiting the maximum energy which can be gained in a single transit. Using modern techniques to suppress secondary particles, Cranberg's square root dependence has given way to an almost linear relation of terminal voltage to column length over the range 5–25 MV.

8.3 Beam Optics

At its simplest, the optical system of an accelerator tube consists of a strong converging entrance lens, a region of uniform longitudinal field and a weak diverging exit lens. Elkind [15] has given algebraic expressions for the first-order focusing and magnification of such a tube. More detailed treatments, using finite-element techniques to calculate field distributions and transfer matrices to handle finite-emittance beams, are due to Galejs and Rose [1] and Stenning and Trowbridge [16], among others.

The strength of the entrance lens depends on the injection energy of the beam and on the field in the tube. In many accelerators the terminal voltage, and consequently the field in the tube, may vary over a range of ten to one. To compensate for this the injection energy, or the position of the tube object, must also vary.

Because space is limited, a terminal ion source is usually close to the tube entrance. The usual practice is to preaccelerate the diverging beam from the source so as to keep the focal conditions constant as the terminal voltage changes. Within the tube, the beam may converge towards an external focus, remain parallel or even diverge slightly as long as it remains smaller than the tube apertures, whose size is limited by the need to intercept the secondary particles that trigger breakdowns. On leaving the accelerator tube, the beam may be refocused by external lenses onto a target or an analyzer magnet, reducing the high magnification that results from the proximity of ion source and tube entrance. The magnification may also be reduced by lowering the field near the tube entrance.

The beam that enters the low-energy tubes of a tandem must be brought to a focus in the stripper, close to the tube exit. Preaccelerating this beam to match it to the tandem over a range of terminal voltages means mounting the ion source on a high-voltage platform. This can be avoided, if space is available, by varying the tube object position with a zoom lens, but at the cost of changing the beam radius at the stripper. The problem can be overcome by the use of a gridded immersion lens at the tube entrance or a gridded einzel lens just before it. Another solution is the use of a “Q snout”, a method of preaccelerating the beam before it enters the main part of the tube.

The entrance lens is the most critical optical element in the tube. It is a strong lens with significant aberration; it operates on a low-energy beam; its aperture radius limits the acceptance. The temptation to inject high-emittance beams which occupy too large a fraction of this aperture is hard to resist. It is therefore important to know how much of the aperture can be filled before aberrations degrade the image or reduce the transmission.

Using modern finite-element field computation programs, Colman and Legge [17] and Trowbridge et al. [18] have calculated aberrations for simple geometries in the absence of space charge. Such programs can be used to improve the electrode geometry before and after the entrance aperture. The exact focal power of the lens is not critical, since this can be adjusted by varying the injection energy or object position. Aberrations, however, increase the emittance of the beam, worsening the size of the beam on target and risking transmission loss.

After stripping, a tandem beam enters the high-energy tubes. At this point it is small in diameter and divergent, but the emittance will have increased owing to scattering, especially for foil-stripped heavy ions. The focusing action of the entrance lens to the high-energy tube is independent of terminal voltage, as the ratio of injection energy to field is constant. But the strength varies with the charge state of the beam, being small for singly charged ions, and more important for high-charge-state heavy ions, where it helps to compensate stripper scattering.

The assumption that the field inside the accelerator tube is uniform is only true if:

(a) the grading resistors are all equal, and
(b) there are no dead sections, and
(c) the electrodes are thin.

Tolerances on high-voltage resistors are rarely as low as 1% and may rise in use to 5–10%. Surge damage can result in even larger decreases and occasionally increases big enough to cause breakdown. The effect of such random changes on beam focus are difficult to calculate but are usually small. But in inclined-field tubes, they may deflect the beam significantly.

Dead sections occur at tube joints but may also be introduced deliberately to modulate the axial field. The radial fields so generated are strong enough to suppress low-energy electrons (and ions), but too weak to have much effect on the main beam.

The focusing action of thick electrodes has been studied by Galejs and Rose [1] and Trowbridge et al. [18]. For typical geometries where $t/p < 0.1$ (t is the electrode thickness and p is the pitch), the effects are small unless low-energy beam particles are allowed to graze the edges of the electrodes.

8.4 Suppression Systems

As accelerator development led to higher terminal voltages, it became imperative to reduce or eliminate the growth of secondary-electron currents. Some success was achieved by tapering the beam apertures in such a way as to intercept at least a proportion of secondaries released within the tube [19]. Another technique, with little to recommend it, was to increase the pressure in the tube so as to scatter low-energy particles onto neighboring electrodes. The first satisfactory answer to the problem was the proposal, by Van de Graaff, to introduce transverse electrostatic fields arranged so as to sweep low-energy particles out of the beam aperture but leave the beam itself undeflected [20]. In Van de Graaff's scheme, a group of electrodes, inclined so as to produce an upward component of the field (in a horizontal accelerator), would be followed by a slightly longer group inclined downwards. By matching the lengths of successive sections to the velocity profile of the beam, the energetic primary beam could be kept close to, and would exit on, the axis. In contrast, electrons born within these sections would be swept onto the electrodes before gaining more than a few hundred keV energy. Only electrons born in the transition regions between upward and downward fields would travel long distances. A typical electrode arrangement in such an inclined-field tube is shown in Fig. 8.8. Allowance must be made, in the alternating-field geometry, for the astigmatic focusing of the slot apertures in the electrodes and the prismatic field at the transitions. These effects have been discussed by Serbinov [21] and Koltay [22].

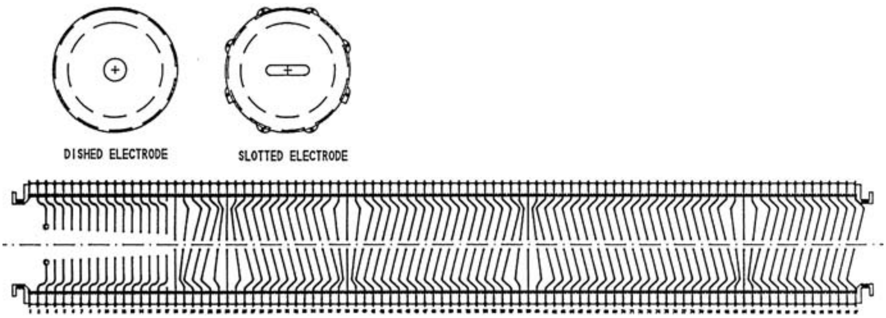
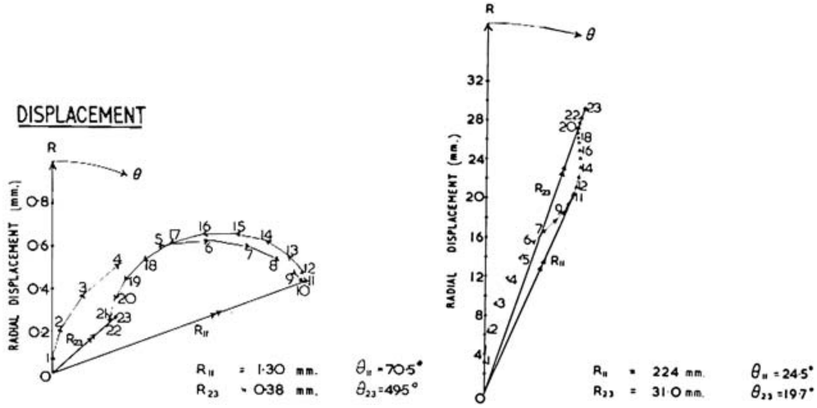


Fig. 8.8. Electrode arrangement of an HVEC inclined-field entrance tube for an MP tandem. The beam enters from the *left* and passes through a noninclined section with circular apertures, then through five inclined-field sections with slotted apertures

At about the same time, Allen [23] proposed an alternative arrangement in which the inclination direction of successive electrodes was rotated azimuthally in such a way as to suppress secondaries. By changing the rate and sense of the azimuthal rotation after each complete turn, the beam could be made to leave on axis and all secondaries could be suppressed, as indicated in Fig. 8.9. As in Van de Graaff's scheme, absolute compensation of the beam displacement is only achieved for a specific velocity profile, but for the range of velocities observed in practice the mismatch is sufficiently small for it to be corrected by external deflectors; see Fig. 8.10. Both schemes depend on a uniform field in the column and are affected by perturbations such as beam loading or damaged resistors.

A little later Howe [25] developed a third system, involving the use of permanent magnets mounted on the electrodes. Originally ring magnets, magnetized across a diameter, were mounted inside the vacuum system to produce a field on axis of $\sim 0.01\,\mathrm{T}$. The field direction rotated on successive



(a) (b)

Fig. 8.9. Transverse displacements of the accelerated beam (**a**) and low-energy secondary electrons (**b**) after traveling through two sections of a spiral inclined-field tube (Reprinted from [24], copyright (1973) with permission from Daresbury Laboratory)

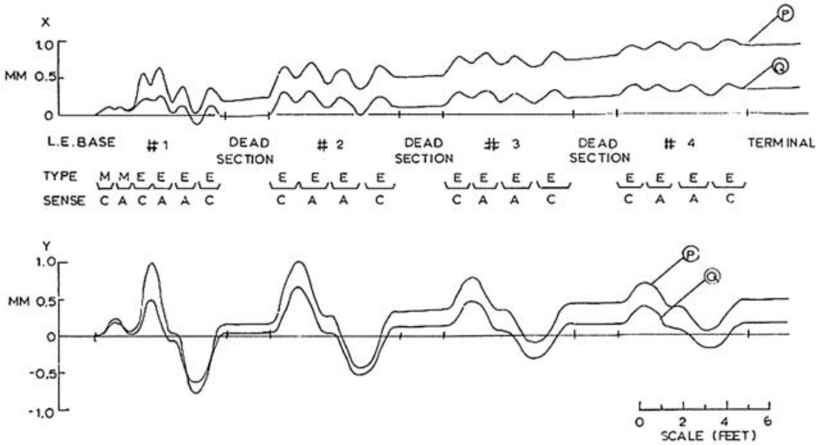


Fig. 8.10. Trajectories of axial rays through the low-energy spiral IF tubes of an MP tandem. Upper figure: horizontal plane. Lower figure: vertical plane. Key: TYPE: M, magnetic section; E, electrostatic section. SENSE: C, clockwise field rotation; A, anticlockwise field rotation. Rays: P, mass = 1, charge = 1−, injection energy = 0.1 MeV, terminal voltage = 12 MV; Q, mass = 1, charge = 1−, injection energy = 0.2 MeV, terminal voltage = 2 MV (Reprinted from [24], copyright (1973) with permission from Daresbury Laboratory)

electrodes so as to cancel the deflection of the beam while ensuring full electron suppression. Because the transverse impulse is independent of velocity, the final transverse momentum of the beam can be nulled for all velocity profiles. In any case, the rather weak fields needed to suppress electrons have a minimal effect on ions. A similar system, using bar magnets mounted on the edges of the electrodes outside the vacuum, has been used with Van de Graaff's inclined-field tubes to improve electron suppression at the transition points. Howe's original ring magnets have long since been replaced by compact high-coercivity Sm–Co or rare-earth bar magnets mounted inside the vacuum envelope.

A very different technique, avoiding the use of transverse fields, has been developed by Herb for the accelerators produced by NEC [26, 27]. The ceramic/titanium tubes used in these machines are made up of short sections joined together by bolted flanges. The axial field therefore varies periodically from a maximum in the middle of each section to a minimum opposite the flange joint. By suitable design of the electrodes on either side of the section joints, the field can be shaped so as to deflect any electrons released from these apertures onto nearby electrodes; see Fig. 8.11. Because the field is axially symmetric, particles on or near the axis will be transmitted, but secondary particles from the electrodes and divergent scattered particles are mostly removed, as shown in Fig. 8.12. High operating fields can be attained if the vacuum is sufficiently good.

Incorporating any of these suppression systems into an accelerator tube complicates the beam optics calculations. Computing the first-order displacement of the beam caused by the alternating or rotating inclined fields of the Van de Graaff or Allen system is straightforward. Assuming the field to be uniform across the beam aperture, it is sufficient to track the path of the axial ray as it passes through the suppression system with a known velocity profile. It is normal practice to start the inclined-field sections after a straight section of 15 to 20 electrodes that is usually magnetically suppressed and operated at reduced gradient. Recently, internal bar magnets have been incorporated in inclined-field tubes and in tubes with axial field modulation in order to reinforce electron suppression.

8.5 Design and Construction

The accelerator tube is a precision device working in a harsh environment. The designer's first task is obviously to ensure adequate mechanical strength. In horizontal machines, the tube is sometimes cantilevered from the base, having to support its own weight and sometimes an ion source and lenses. In horizontal tandems, tubes as long as 2.4 m will be simply supported solely at their ends. In vertical machines, the weight of the whole tube and the pressure of the gas will bear on the base of the tube. The insulators must also resist

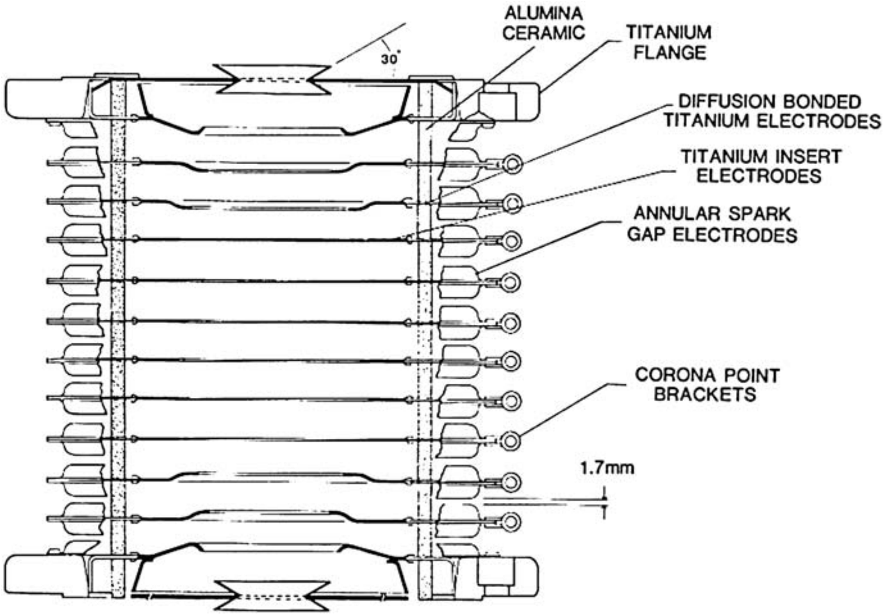


Fig. 8.11. NEC "compressed-geometry" tube section designed for the Oak Ridge 25 MV tandem, showing the shaped electrodes at the section ends that determine the electron-suppressing fields (Reprinted from [27], copyright (1988) with permission from Elsevier)

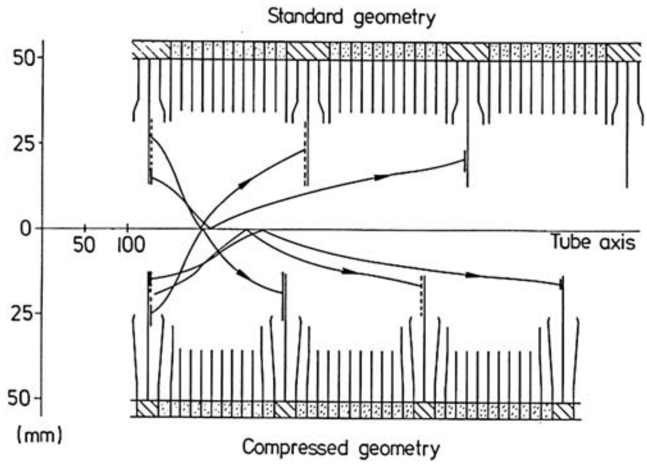


Fig. 8.12. Electron trajectories in standard and compressed-geometry NEC tubes operating at a gradient of 330 kV per tube section. Secondary electrons released from the end electrodes are captured on subsequent end electrodes before gaining excessive energy (Reprinted from [26], copyright (1984) with permission from Elsevier)

the radial force due to gas at pressures of up to 2 MPa. Deflections resulting from the cyclical variation of gas pressure must be small and reversible, consistent with the accuracy required by the beam optics. The overall length and diameter must be compatible with the layout of the column and the need for access for installation, assembly and maintenance.

The choices of materials and of the detailed design of insulators and electrodes have been made in the light of the operating conditions and physical processes already described. Vacuum conductance is clearly of major importance. The tube must tolerate variations in temperature, humidity and pressure during transport. In service, it must withstand mechanical shock during tank sparks and occasionally tremors due to earthquakes.

8.5.1 Insulators

The superior vacuum properties of glass and ceramics ensure their use in preference to plastic insulators, although these have adequate dielectric strength and resistivity.

The relevant properties of the two most widely used materials are summarized in Table 8.1. The better electrical properties of glass, coupled with adequate mechanical strength, would make it always the material of choice if it were not for the possibility of making ultra-high-vacuum, organic-free, bonds between alumina and titanium.

Table 8.1. Properties of tube insulators. Note: dielectric strengths were measured on 3 mm samples; see Aitken [28]

Insulator	Borosilicate Glass	High-density Alumina
Thermal expansion ($^\circ C^{-1}$)	3.8×10^{-6}	7.6×10^{-6}
Elastic modulus (GN/m^2)	68	344
Breaking strength (MPa)	35–140	360
Log volume resistivity (Ω cm)	$>10^{15}$	$>10^{14}$
Dielectric constant	4.2	9.5
Dielectric strength (MV/m)	120–180	50–70
Secondary-emission coefficient	3 (max) at 350 eV	8 (max) at 600 eV

Glass insulators are made from castings that can be inspected optically for bubbles, strings (of impurity) and freedom from stress. After annealing, they are ground flat on both end surfaces and on the interior, usually to a profile designed to increase tracking length and minimize surface charge. Flatness is carefully controlled so as to ensure uniform glue film thickness. The most usual pitch is 25 mm, but larger pitches have been specified for tubes working at modest fields. Diameters range from $\sim$100 mm in some small accelerators to over 300 mm for large machines and in applications where good vacuum is critically important.

Ceramic insulators are made from pressed high-density alumina, which is then sintered at high temperature and ground flat on the ends. Control of the manufacturing process is very important in order to avoid small voids that may not be revealed by nondestructive tests. Most tubes using ceramic insulators have a pitch of 12.7 mm and a diameter of about 100 mm. The small pitch is beneficial in reducing the energy acquired by ions in interelectrode processes and in reducing the influence of the high secondary-emission coefficient on surface charging. The maximum safe diameter is limited by the differential thermal expansion between ceramic and metal and the high temperature used in the bonding process.

8.5.2 Electrodes

In the past a variety of metals have been used in accelerator tubes, including copper, which is easily cleaned and polished, and refractory metals such as molybdenum, which resist sputtering and melting in discharges. Experience gained in extensive laboratory tests, combined with the need to reduce bremsstrahlung by using materials of low atomic number, have made stainless steel and titanium the preferred choice, with aluminum a low-cost alternative for applications where heavy ion bombardment and arcing can be discounted. The relevant properties are shown in Table 8.2.

Table 8.2. Properties of tube electrodes

Electrode	Aluminum	Stainless Steel	Titanium
Atomic number	13	26.2	22
Thermal expansion ($^\circ C^{-1}$)	2.3×10^{-5}	9.3×10^{-6}	7.6×10^{-6}
Elastic modulus (GN/m^2)	69	193	110
Yield strength (MPa)	145	760	830
Melting point ($^\circ C$)	660	1530	1800
Plastic velocity (m/s)	320	530	1200

In early accelerator tubes, the long pitch of the insulators and difficulties in achieving clean vacua encouraged the designers to resort to complex re-entrant shapes for the electrodes so as to prevent scattered particles hitting the insulators and eliminate interactions between the beam and the surface charges. In today's designs, electrodes are usually thin and, if not actually flat, pressed into a dish shape or inclined at an angle to sweep secondary particles off axis. Sometimes the electrode is in two parts: a flat annulus bonded on either side to the insulator, and a removable, central insert that defines the beam aperture, intercepts unwanted secondaries and can be removed for cleaning. The aim is always to keep the peak field between adjacent electrodes as low as possible. The outer part of the electrode must be flat enough or flexible enough to ensure a strong, vacuum-tight bond without voids. Aluminum electrodes are 2–3 mm thick, stainless steel and titanium electrodes 0.5–1.0 mm. The electrodes normally extend a few mm beyond the outer edge of the insulator and carry protective spark gaps. These may consist of six or more sphere gaps, 3–4 mm in radius, uniformly disposed around the circumference, or a pressed ring forming an annular gap close to the outside of the insulator. The spark gaps are set to break down at a slightly lower voltage than the gaps protecting the column, the actual setting depending on the rated field in the column and the expected gas composition and pressure.

8.5.3 Assembly

Tubes with glass insulators use thermoplastic resin, usually polyvinyl acetate, as a bonding material. The resin is dissolved in a suitable solvent and a controlled quantity is then deposited on both sides of the electrodes. After solvent evaporation, the end flanges, insulators and electrodes are stacked in a jig, heated in a tube oven to the softening point of the resin, compressed and then allowed to cool slowly at a controlled rate. The jig is designed to keep the tube straight and accurately aligned. The heating and cooling cycle ensures that strain, locked into the assembly because of differential thermal expansion, is kept to a minimum. Tubes as long as 2.4 m can be assembled in a single operation. A single section therefore suffices for accelerators rated at 3 MeV or even more.

Ceramic/titanium tubes rely on diffusion bonding. In this process aluminum foil, 0.1 mm thick, is cut to the same shape as the insulator ring and interposed between insulator and electrode. Assemblies, typically containing 13 insulators and electrodes, and titanium end flanges, are then jigged and placed in an oven, in which they are compressed and held at a temperature just below the melting point of aluminum. In time, the aluminum diffuses into the ceramic to form a strong, vacuum-tight bond. The temperature cycle, compressive force and ambient gas are all tightly controlled. The short length of single sections requires that all but the smallest machines will incorporate several units, introducing dead sections into the column.

8.6 Vacuum

Vacuum conditions affect tube performance in several ways. Beam losses due to scattering with residual gas are important for very intense beams, since the scattered particles may load the column and upset the gradient. Vacuum conditions are also critical where negative ions are injected, because they have large cross sections at low energy for charge exchange. The problem is especially acute in accelerator mass spectrometry, where loss-free transmission is needed for accurate measurement of isotopic intensities. Low residual pressure is also desirable because it reduces the amount of adsorbed gases on electrodes and hence the frequency and intensity of microdischarges. Finally, the composition of the residual gas has an important influence on the production of sputtered ions and hence on the threshold for microdischarge activity.

Cockcroft and Walton were among the first users of the low-vapor-pressure hydrocarbon oils developed by Metropolitan-Vickers for diffusion pumps. However, backstreaming oil vapor was soon under suspicion as a cause of electron emission and was successively replaced as a working fluid in accelerator applications by mercury, which required trapping with liquid air, then by silicon-based fluids, and more recently by polyesters and other fluids with very low vapor pressures and improved resistance to chemical attack. These new fluids have led to a reduction in ultimate pressure of two orders of magnitude, but they pose the risk of contaminating the tube in a vacuum accident. In contrast to hydrocarbons, which form conducting surface layers, silicone oils act as insulators and can upset the functioning of high-voltage electrodes by allowing surface charges to build up and distort the field.

Complete freedom from oil contamination can be achieved at high vacuum by the use of cryopumps or sputter ion pumps. Initial evacuation requires the use of sorption traps or, more conveniently, hybrid turbomolecular/drag pumps, whose high compression ratio for heavy molecules ensures negligible backstreaming. In practice, modern turbomolecular pumps, even those with greased bearings, release negligible oil vapor and can be used as recirculators in high-voltage terminals.

It is very easy to fit a high-speed pump outside the accelerator tank and measure very low pressures above it. But gas sources inside the accelerator, such as ion source or stripper gas in the terminal, and outgassing and desorption anywhere, must be pumped through the meager conductance of the tubes. What matters is the pressure near the terminal, and this may be as much as fifty times higher than that at the pump. The need to limit the path of secondary particles means that most tubes have baffle electrodes that reduce the conductance well below that of a simple tube of the same I.D. For example, the conductance of a standard 1.8 m tube with a central aperture tapering from 63 to 38 mm radius has been measured to be 47 l/s. A more realistic design for a single EN tandem tube, having a central aperture of 12.5 mm radius and additional pumping sectors arranged as in Fig. 8.13, has a measured conductance of 21 l/s. With such tubes, a pressure rise of 10^{-4} Pa at the pump, due to stripper gas, corresponds to a pressure of at least 3×10^{-3} Pa at the terminal, making no allowance for outgassing along the length of the tube. Even higher pressures exist in single-ended machines. In large accelerators, such as MP tandems and NEC machines, the column is punctuated by substantial dead sections, and electrical power is available in some of these locations to energize sputter ion pumps. Conductances and pressure profiles for the large VIVITRON tandem at Strasbourg were reported by Heugel [29].

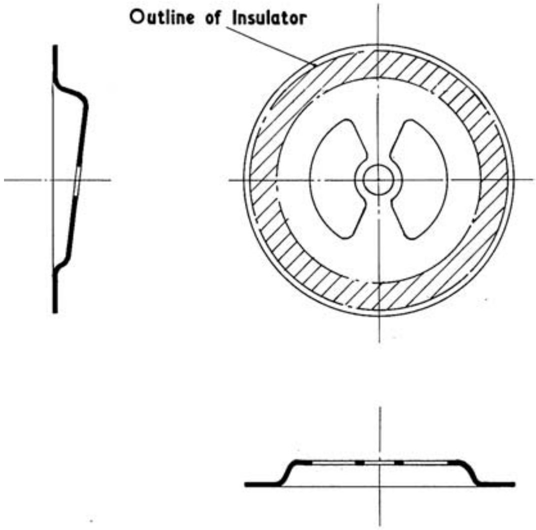


Fig. 8.13. Sections of a spiral IF tube electrode for a model EN tandem, showing pumping cutouts. The measured vacuum conductance of a single 1.8 m section is 21 l/s

His work emphasizes the gradual improvement in vacuum resulting from the slow decrease in outgassing rate with time.

The need for terminal pumping in large tandems has long been recognized. Sublimation pumps, cryopumps and sputter ion pumps have all been used, with varying degrees of success. Sublimation pumps have limited life and a low pumping speed for inert gases. Cryopumps are bulky and require regeneration, involving passage of all the pumped gases through the tubes. Sputter ion pumps have proved to be reliable and long-lived, provided the gas load is kept low. The use of turbomolecular pumps as stripper gas recirculators was suggested by Purser and Hyder in 1982 [30] and has subsequently been applied to reduce the gas load from terminal ion sources. In some high-current single-ended machines, attention has turned again to the provision of differential tubes, through which most of the gas generated in the terminal can be diverted away from the beam path. Satisfactory designs for such tubes, combining a high conductance with effective electron suppression, have enabled them to return to favor.

8.7 Operating Conditions

Tubes are usually shipped sealed and evacuated to ensure cleanliness and freedom from contamination and should remain so as long as possible. PVA is hygroscopic, and there are reports of glued joints deteriorating when kept in humid conditions for long (10 years) periods. During installation, tubes are often exposed to atmosphere for long periods while assembly and alignment take place. Good practice then requires that they should be evacuated for as long as possible before voltage is applied. The use of a residual-gas analyzer, if one is available, helps to distinguish between normal outgassing and a leak. In air, the relative intensity of the mass 28 and mass 32 peaks is a useful diagnostic. A leak-tight tube in an accelerator insulated with SF_6 may still exhibit a very small mass 127 peak, but if this varies with pressure the leak must be cured before voltage is applied. It is equally important to ensure that the grading resistors are all within specification.

Initial conditioning is an important process that should only be undertaken when the necessary controls and instruments are fully operational and the electrostatic behavior of the accelerator is satisfactory. The progress of conditioning can be monitored by measuring vacuum pressure, radiation, current balance and particle emission. Typically, the voltage can be increased steadily up to about half the rated maximum before microdischarge activity results in a measurable increase in vacuum pressure. If the voltage is then held constant, the pressure should decrease, almost to the base value. Small fluctuating ion or electron currents may be observed on Faraday cups close to the tube, and radiation levels may rise above background. These effects should also decay away if the voltage is held constant. The normal procedure is next to increase the voltage in small steps, limiting the pressure rise to a few times the base pressure and pausing if the ion currents or radiation levels become erratic. Ideally this sequence should continue until the tube is operating quiescently at or above its rated voltage. In low-voltage accelerators with lead-shielded tanks, external radiation levels may be very low and conventional radiation monitors may need to be supplemented by a gamma spectrometer. In larger machines, the use of a mobile spectrometer may give valuable information about the energy and origin of abnormal sources of bremsstrahlung. Viewing ports can reveal the intensity and distribution of luminosity from microdischarges.

Conditioning to full voltage necessarily involves a higher probability of sparking than does quiescent operation. The risk of damage is much greater in large machines because of the strong dependence of stored energy on voltage. The risk of sparking is also greater because of the chance that many microdischarges will occur simultaneously in different tube sections, leading to excessive pressure rises. The use of shorting rods or cables, enabling individual sections to be taken to voltage with a small fraction of the stored energy of the whole machine, has proved effective in raising the voltage safely in multisectioned machines. Another technique, which is useful in machines of all sizes, is to apply a sawtooth waveform by computer control of the charging current. A typical amplitude for this process is 1–2% of full voltage, with a period long enough for the vacuum to return to normal between peaks.

A tube which has been conditioned to maximum voltage and then operated with beam at or very near that voltage is in a state of dynamic equilibrium. As residual gas is readsorbed on surfaces previously cleaned by microdischarges, the condition for further discharges returns. Small ion currents will flow intermittently, depleting the surface gas layers at the same rate as the readsorption. Adsorbed gas will build up when the voltage is removed and must be removed by reconditioning before returning to full voltage. Contaminants and molecules not present in the residual gas are, however, permanently removed and tube performance will improve in consequence.

Accelerator tubes operating with intense beams near the maximum voltage are at risk of damage if the beam disappears or becomes defocused. In the former case interlocks are required to sense beam loss and take effective corrective action to stop the voltage rising. If the beam becomes defocused, it must be stopped at the tube entrance and the terminal voltage frozen.

Diagnosing tube faults is a demanding part of the operator's duties. Tubes may fail because of internal defects or because of external faults such as vacuum leaks or open-circuit resistors. It is very desirable to establish the nature and location of the problem before the tank is opened, since the symptoms are likely to disappear when the voltage is removed and the gas pressure reduced. Breakdown across an individual insulator very often manifests itself as a sawtooth variation in terminal voltage and particle energy. The amplitude of this fluctuation, as seen by a capacitive pickup looking at the terminal, decreases the farther the faulty section is from the terminal. If the problem is near the baseplate, the long time constant of the terminal capacitance and the column resistors may attenuate it so much as to make it undetectable. Such failures may also generate increased bremsstrahlung with a measurable maximum energy, enabling the source to be identified. Viewing ports opposite the column can be used to reveal sparking or luminosity at the site of the problem.

Another class of faults arises when column gradients are perturbed by radiation, leakage currents or faulty resistors. Attempts to hold the terminal voltage constant then result in the unaffected part of the column being overstressed. If the original fault occurs near an inclined-field tube the gradient error will deflect the beam sideways, sometimes far enough for total beam loss, beyond the correcting power of external deflectors.

Vacuum faults are often signaled by the onset of severe conditioning at abnormally low voltage. Pressure-sensitive leaks, especially of SF_6, degrade tube performance and may require prolonged conditioning before recovery. Tubes severely contaminated by oils or polymers must usually be removed and reconditioned or rebuilt.

The low-energy X-rays always present inside accelerator tubes are partly absorbed in the tube wall. In glass, this causes darkening due to the formation of color centers. After prolonged operation the glass may become completely opaque, but without any deterioration of its insulating properties. Ceramic insulators also can sustain this type of radiation damage without detriment.

In the absence of vacuum accidents, contamination and external faults, well-protected tubes can continue to operate normally for ten years or more.

8.8 Conclusions

The modern accelerator tube has come a long way towards fulfilling the requirements outlined in Sect. 8.1. With proper protection it can survive undamaged in the largest electrostatic accelerators, operating at full voltage. It can be brought up to its rated voltage with modest conditioning in a well-defined way. Its focal properties can be predicted accurately; ion currents at mA levels can be transmitted with negligible loss through small machines; multiply charged heavy-ion beams of tens or hundreds of μA are available from large tandems. Small accelerators working below the neutron threshold can be operated in unshielded rooms, with a modest layer of lead surrounding the tank. Voltage stability, vacuum quality, suppression of impurity ions and beam transmission can all meet the challenges of ultrasensitive mass spectrometry and advanced ion implantation.

However, even the best tubes cannot be made to work satisfactorily at fields much in excess of 2 MV/m. At these gradients, surface charges on insulators and ion exchange between electrodes begin to affect stability and increase the probability of breakdown. Experiments have been carried out at 11 MV in an FN tandem, corresponding to a field of 2.25 MV/m over the active length of the tube. The NEC tandem at the Australian National University, Canberra, has been conditioned to 2.6 MV/m and has run experiments at 2.4 MV/m [31]. A few small accelerators have operated at slightly higher fields. In most applications, the length of the tube is not critical. A conservative tube gradient is a small price to pay for ease of operation and reliability.

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